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Published in:

Program and Abstracts of the XXI Congress, International Society of Biomechanics

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Document Version

Publisher's PDF, also known as Version of record

Publication date:

2007

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Zhang, X., Li, K., & Vakis, A. I. (2007). Biological Inspiration from Dynamic Modeling of Human Hand and Trap-Jaw Ant Mandible Movements. In *Program and Abstracts of the XXI Congress, International Society of Biomechanics* (Vol. 40, pp. S79-S79). University of Groningen, Research Institute of Technology and Management.

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Biological Inspiration from Dynamic Modeling of Human Hand and Trap-Jaw Ant Mandible Movements

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INTRODUCTION

Biodynamic models of the neuro-musculo-skeletal system in movements remain to be prime vehicles for pursuing basic knowledge about the system. Models are perhaps still the only means to generalize and reconcile experimental studies. When implemented as computer simulations, they can enable applications such as computer-assisted orthopedic surgery or rehabilitation, VR-based medical training etc. The model development process can render insight and inspiration for technological innovations to restore or augment human physical capabilities.

This presentation will delineate the musculoskeletal dynamic modeling of two drastically different movement acts: volitional, complex multi-fingered human hand movements, and extremely fast, simple trap-jaw ant mandible strike movements. We aim to understand the fundamental mechanisms that allow the efficient control of complex yet coordinated multi-fingered hand movements, and the extraordinary motion production in trap-jaw ant mandible strikes; we seek quantitative understanding to help advance the developments of new hand prostheses, bio-robots, and biomimetic micro-devices. In addition, we are interested in viewing this work as a comparative study to explore whether a unifying framework can be applied to the modeling of two biologically and mechanically contrasting movements.

METHODS

The movement data were acquired in previous studies by our group [1] and our collaborators [2]. Measurement of multi-fingered hand movements involved use of an optical system capturing at 120 Hz the retro-reflective markers strategically placed on the dorsal side of subjects' hands [1]. The trap-jaw ants' mandible strike movements, arguably the fastest biological motions ever recorded, were measurable only using an ultra-high-frequency (50k-84k Hz) imaging system [2]. Recorded hand surface landmark coordinates or digitized mandible feature point locations were analyzed to derive the angle-domain data and to construct skeletal representations (Figure 1).

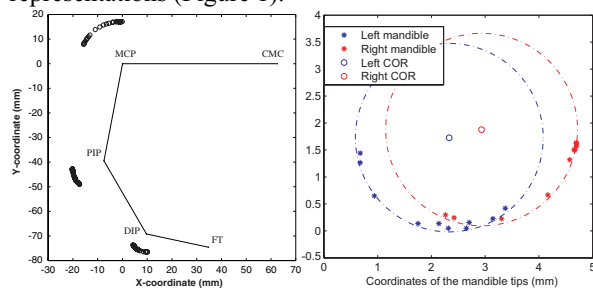


Figure 1: Kinematic analyses of movement data acquired.

A two-stage dynamic modeling approach is proposed to make the computation more tractable, and to elicit additional information about system dynamics and control. The first stage relates the joint torques to the measured kinematics and uses a system identification procedure to estimate system

parameters including dynamic damping and stiffness properties. It entails a least-squares search routine that identifies the parameters empirically. The second stage maps the musculotendon forces to the joint torques, which requires the musculoskeletal geometry data from the literature [3, 4], and our μ -CT and μ -MRI measurements of the trap-jaw ants' morphological characteristics.

RESULTS AND DISCUSSION

Our models reproduce the measured kinematics accurately. The predicted joint torque and muscle force magnitudes during multi-fingered hand movements seem to agree with values reported in the literature (Figure 2).

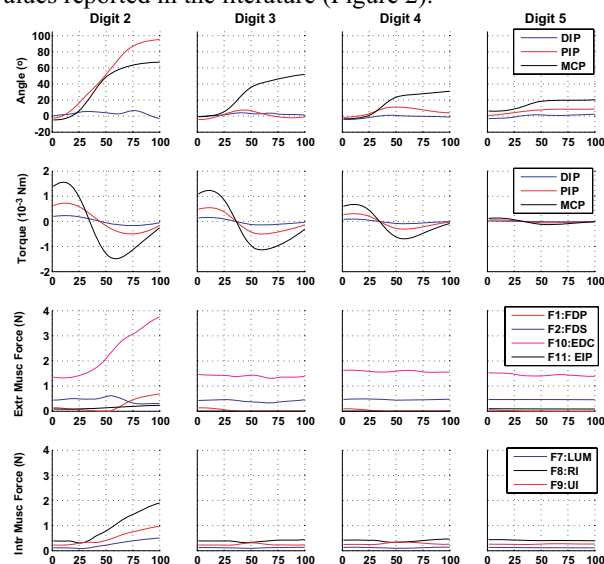


Figure 2: Representative kinematics, torque, and muscle force profiles during an individuated index finger flexion.

CONCLUSIONS

So far, we are able to use a common framework and general protocol for musculoskeletal dynamic modeling of two distinctly different biological movements. Aspects such as neural excitation input and control feedback however remain unexplored. We demonstrate that models can reconcile in vivo and in vitro studies and integrate the findings in a most logical way. This is especially valuable when experimental data acquisition is limited. Multi-finger movements exhibit stereotypical patterns in joint torques, muscle/tendon forces both within and across individual digits. The correlations or invariants embedded in these patterns are being quantified to guide new development of more dexterous multi-functional hand prostheses. The remarkable biomechanical capabilities of trap-jaw ants, once understood, can inspire the advent of exquisite self-sustained fast-acting systems.

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